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Original article

Influence of the Sphero-Cylindrical Tool Orientation Angles on Roughness under Processing Complex-Profile Surfaces

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Abstract

Introduction. When milling complex-profile surfaces of parts, the selection of tool trajectories and orientations affect the roughness parameters. However, in the studies devoted to the formation of trajectories, recommendations to provide the quality of microgeometry of surfaces were not taken into account. Moreover, when writing programs for CNC equipment in CAM systems, the limitations of cutting modes were determined exclusively using a geometric approach. It did not take into account the influence of the orientation angles of the sphero-cylindrical tool relative to the normal plane on the quality of surface treatment, namely on roughness. The work was aimed at the creation of the methodology for selecting the limiting values of the orientation angles of a sphero-cylindrical tool to optimize the process of machining spatially complex surfaces. The tasks included achieving the minimum values of the amplitude roughness parameter *Rz* and determining the effectiveness of various machining paths.

Materials and Methods. Methods of correlation and regression analysis were used, the results were compared and generalized. The least-squares method was applied to estimate the parameters of the regression equation. The DMU 50 ecoline processing center was used for the experimental studies. Roughness was measured on a Surfcam 1800 D profilometer. The material of the samples was steel 12X18N10T. The material of the tool was hard alloy 1620 Sandvik with PVD coating (physical vapor deposition, the closest domestic analogue is T15K6).

Results. It has been shown in detail how roughness parameters *Rz* depend on the angle of inclination and the diameter of the tool. Twenty examples were summarized in a table. Natural regression coefficients were calculated using linear and hyperbolic models. It was found that the diameter of the tool had a greater effect on the formation of roughness parameter *Rz* than the angle of inclination. For a detailed description of the influence features, the coefficients of multiple, partial, paired correlation and multiple determination were compared. The limitations associated with the angles of inclination of the tool when processing complex surfaces were determined. A scheme for calculating the angle of the normal was visualized, which included the selected step along the axis to determine the lengths of the segments of the broken curve. The profilograms of surfaces obtained with different shaping trajectories were given in the form of drawings. This allowed us to conclude that milling from top to bottom is unsuitable when the tool is tilted 5°–35°. A map has been compiled by which it is possible to judge the roughness, knowing the type of milling and the inclination angle (from 5° to 80°). The dependence of the roughness parameter on the processing speed and the use of coolant was represented graphically. The calculated parameters for determining the optimal angle of inclination of the tool were tabulated. Their analysis proved the adequacy of the proposed method of preparing control information.

Discussion and Conclusion. The presented technique made it possible to determine the optimal values of the orientation angles of the sphero-cylindrical tool. taking into account the cutting speed and the minimum possible amplitude roughness parameter *Rz*. The pattern of feeding fz = 0.4 mm/tooth for surface areas with a total angle of

5–50° was considered. In this case, processing along trajectories in the passing, opposite and bottom-top directions, provided roughness in the range of 3–6 μm according to parameter *Rz*. The top-down toolpath is not recommended for use in final operations due to the significant height of parameter *Rz*.

Keywords: amplitude roughness parameter, orientation of a sphero-cylindrical tool, milling of complex-profile surfaces, spatially complex surfaces

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Научная статья

Влияние углов ориентации сфероцилиндрического инструмента на шероховатость при обработке сложнопрофильных поверхностей

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Аннотация

Введение. При фрезеровании сложных поверхностей деталей выбор траекторий и ориентации инструмента влияют на параметры шероховатости. Однако в исследованиях, посвященных формированию траекторий, не учитываются рекомендации, позволяющие обеспечить качество микрогеометрии поверхностей. К тому же при написании программ для оборудования с ЧПУ в CAM-системах (от англ. computer-aided manufacturing — автоматизированное производство) ограничения режимов резания определяются исключительно с помощью геометрического подхода. Он не учитывает влияние углов ориентации сфероцилиндрического инструмента относительно плоскости нормали на качество обработки поверхностей, а именно на шероховатость. Цель работы — создание методики по выбору предельных значений углов ориентации сфероцилиндрического инструмента для оптимизации процесса механической обработки пространственно-сложных поверхностей. Задачи: достижение минимальных значений амплитудного параметра шероховатости *Rz* и определение эффективности различных траекторий обработки.

Материалы и методы. Использовались методы корреляционного и регрессионного анализа, результаты сравнивались и обобщались. Для оценки параметров уравнения регрессии применялся метод наименьших квадратов. Для экспериментальных исследований задействовали обрабатывающий центр DMU 50 ecoline. Шероховатость измеряли на профилометре Surfcom 1800 D. Материал образцов — сталь 12Х18Н10Т. Материал инструмента — твердый сплав 1620 Sandvik с PVD-покрытием (от англ. physical vapor deposition — физическое осаждение паров металлов. ближайший отечественный аналог — Т15К6).

Результаты исследования. Детально показано, как параметры шероховатости *Rz* зависят от угла наклона и диаметра инструмента. Двадцать примеров представлены в виде таблицы. Естественные коэффициенты регрессии рассчитаны по линейной и гиперболической моделям. Установлено, что диаметр инструмента больше влияет на формирование параметра шероховатости *Rz*, чем угол наклона. Для детального описания особенностей влияния сравнивались коэффициенты множественной, частной, парной корреляции и множественной детерминации. Определены ограничения, связанные с углами наклона инструмента при обработке сложных поверхностей. Визуализирована схема для расчета угла нормали, которая включает выбранный шаг по оси для определения длин отрезков ломаной кривой. Даны в виде рисунков профилограммы

поверхностей, полученные при различных траекториях формообразования. Это позволило сделать вывод о непригодности фрезерования сверху вниз при наклоне инструмента 5°–35°. Составлена карта, по которой можно судить о шероховатости, зная вид фрезерования и угол наклона (от 5° до 80°). Графически показана зависимость параметра шероховатости от скорости обработки и применения охлаждающей жидкости. Сведены в таблицу расчетные параметры для определения оптимального угла наклона инструмента. Их анализ доказал адекватность предложенного метода подготовки управляющей информации.

Обсуждение и заключение. Представленная методика позволила определить оптимальные значения углов ориентации сфероцилиндрического инструмента с учетом скорости резания и достижения минимально возможного амплитудного параметра шероховатости *Rz*. Рассмотрена ситуация подачи *fz* = 0.4 мм/зуб для участков поверхности с суммарным углом 5º–50°. В этом случае обработка по траекториям в попутном, встречном направлении и снизу вверх обеспечила шероховатость в диапазоне 3–6 мкм по параметру *Rz*. Траектория движения сверху вниз не рекомендована к применению на окончательных операциях из-за значительной высоты параметра *Rz*.

Ключевые слова: амплитудный параметр шероховатости, ориентация сфероцилиндрического инструмента, фрезерование сложных поверхностей, пространственно сложные поверхности

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Introduction. The reliability of machine parts is determined by such performance properties (PP) of surfaces as wear resistance, tightness, strength, quality of coatings [1]. These PP depend on the physico-mechanical and geometric parameters of functional surfaces, including roughness [2–4].

The analysis of the scientific literature suggests a growing interest in the topic of providing the necessary roughness parameters due to the reasonable selection of trajectories of shaping movements and orientation of the sphero-cylindrical tool when milling spatially complex surfaces (SCS) [5–7]. Examples of such parts are forming elements of die tooling, master models for casting, executive surfaces of gearing [8–10].

A number of authors studied the influence of strategies under the milling of SCS and methods of optimizing machining [10–12]. However, knowledge about the formation of trajectories does not take into account the recommendations for providing the quality of microgeometry of the surfaces of the part. It should also be noted that when creating programs for CNC equipment in CAM systems, the limitations of cutting modes are determined exclusively using a geometric approach [13, 14]. It does not take into account the influence of the orientation angles of the sphero-cylindrical tool relative to the normal plane on the quality of surface treatment, namely on roughness. The method of selecting the angles of tool orientation based on empirical models can overcome these disadvantages. Its advantages:

– influence of the tool orientation angles on the surface roughness is taken into account;

– ability to reasonably select processing paths is supported.

The study was aimed at the creation of a methodology for selecting the limiting values of the orientation angles of a sphero-cylindrical tool to optimize the process of machining spatially complex surfaces. The tasks included achieving the minimum values of the amplitude roughness parameter *Rz* and determining the effectiveness of various machining trajectories.

Materials and Methods. Thus, CAM systems provide forming multi-coordinate machining trajectories with tracking of additional parameters, such as collisions, the point of contact between the tool and the part, etc. The sphero-

cylindrical tool touches the part at point P_i (x_i. y_i. z_i) = P_d (x_d. y_d. z_d). At the same time, it is required to avoid machining with the center of the cutter and orient the tool with an angle of inclination of at least 5°–15°.

In the final operations, the effective cutting speed is determined by the effective diameter. At an equal rotational speed, it grows with the increase in the angle of inclination of the tool to the workpiece. An increase in the cutting speed generally causes a decrease in the microhardness of the surface, and with an increase in $V > 75$ m/min, the microhardness parameters change slightly [12]. The dissipation rate strongly depends on the cutting speed and the volume of the material being removed; therefore, cutting-tool lubricant (CTL) is needed to intensify the cutting process [15].

For the experiments, technological equipment with CNC was used, a five-axis machining center DMU 50 ecoline with a maximum spindle frequency of 8,000 rpm. The surface roughness was measured by a Surfcom 1800 D profilometer. Sandvik end mills of the R216 series were used for processing 12X18H10T steel. The material was hard alloy 1620 with PVD coating (the closest domestic analogue is T15K6). The diameter was 8 mm, the number of teeth — 2. To provide a uniform allowance (a_p = 0.2 mm), mechanical treatment with sphero-cylindrical cutters was carried out before the final milling operation.

Research Results. Before determining the angles of inclination, it was required to establish how variable factors affected the response function. In this case, we are talking about the surface roughness according to parameter *Rz* (μm). To find empirical mathematical models of milling with a sphero-cylindrical tool, we took the independent variables: X_1 — diameter (*D*, mm) and X_2 — the angle of the tool inclination (γ, °). The initial data for the analysis were considered in previous studies (when applied to tooth f_z = 0.4 mm/tooth) [16–19] (Table 1).

Table 1

Roughness parameters *Rz* depending on the angle of inclination and diameter of the tool

Angle, °	Tool diameter, mm			
	6	8	10	12
10	9.33	7.66	5.99	4.33
20	8.59	7.06	5.53	4.01
30	7.85	6.46	5.07	3.69
40	7.11	5.86	4.61	3.37
50	6.37	5.26	4.15	3.05

Based on theoretical data on significant factors affecting roughness, linear (1.1) and hyperbolic (1.2) models were adopted:

$$Rz = Y = a + b_1 X_1 + b_2 X_2, \tag{1.1}$$

$$Rz = Y' = a' + b_1 X_1 + \frac{b_2'}{X_2'}. \tag{1.2}$$

Here are the calculated natural regression coefficients: $a =$ 13.37; $a' = 10.25$; $b_1 = -0.66$; $b_2 = -0.58$; $b_2' = 0.51$.

The parameters of the two-factor regression equation were estimated using the standard least squares method; therefore, for simplicity of presentation, we omitted the formulas indicating the coefficients. Standardized β-coefficients: $\beta_1' = -0.79$; $\beta_2 = -0.58$; $\beta_2' = -0.51$. Comparison of the modules of the values of standardized regression coefficients β allowed us to conclude that factor X_1 (tool diameter) had more effect on the formation of the roughness parameter *Rz* than X_2 (inclination angle). Coefficients of multiple, partial, paired correlation and multiple determination:

$$R_{YX_1X_2} = 0.98;\ r_{YX_1X_2} = -0.98;\ r_{YX_2 \cdot X_1} = -0.97;\ r_{X_1X_2 \cdot Y} = -0.95;$$

$$R_{Y'X_1X_2'} = 0.95;\ r_{Y'X_1 \cdot X_2'} = -0.93;\ r_{Y'X_2' \cdot X_1} = 0.85;\ r_{X_1X_2' \cdot Y'} = 0.79;$$

$$r_{YX_1} = -0.79;\ r_{YX_2} = -0.58;\ r_{X_1X_2} = 0.00;\ r_{YX_2'} = 0.51;$$

$$r_{X_1X_2'} = 0.00;\ R^2(Y) = 0.95;\ R^2(Y') = 0.90.$$

Comparing the coefficients, we drew the following conclusions.

When factor X_2 was fixed at a constant level, factor X_1 most strongly affected (|0.98| > |0.79|). When comparing the coefficients of the hyperbolic model, (|0.93| > |0.79|).

When factor X_1 was fixed, the effect of factor X_2 on Rz increased for both models: linear |0.97| > |0.58|, hyperbolic |0.93| > |0.51|.

To ensure the uniformity of the microrelief of the surface, the dependence of the feed and the effective diameter of the tool (D_{cap}) was established, which varied depending on the angle of processing. We defined the limitations associated with the angles of the tool inclination when processing the SCS. To do this, the surface of the part was to be divided into sections and the normal angles calculated. If $z = f(x. y)$, then, in general, the orientation of the tool to the surface was set by selecting the direction of the normal.

At $\cos\gamma = 1 / |N|$:

$$N = \left(-\frac{\delta f}{\delta x}, -\frac{\delta f}{\delta y}, 1\right). \tag{2.1}$$

At $\cos\gamma = -1 / |N|$:

$$N = \left(\frac{\delta f}{\delta x}, \frac{\delta f}{\delta y}, -1\right). \tag{2.2}$$

To determine the inclination angle of the tangent plane, the following equation was used:

$$\tan\alpha = \left|grad(z)_A\right| = \sqrt{\left(\frac{\delta z}{\delta x}\right)^2 + \left(\frac{\delta z}{\delta y}\right)^2}, \tag{3}$$

where $\alpha = |90° - \gamma|$.

AV Nikitenko [20] presented a model for optimizing the orientation angle of a part with corrective angles of inclination A and B relative to X and Y axes:

$$\tan\alpha' = \sqrt{\left(\frac{\delta z}{\delta x} + \tan B\right)^2 + \left(\frac{\delta z}{\delta y} + \tan A\right)^2}. \tag{4}$$

For a special case (Fig. 1), determination of angle λ to normal N:

$$\lambda = \arctan\frac{\Delta z}{\Delta x}. \tag{5}$$

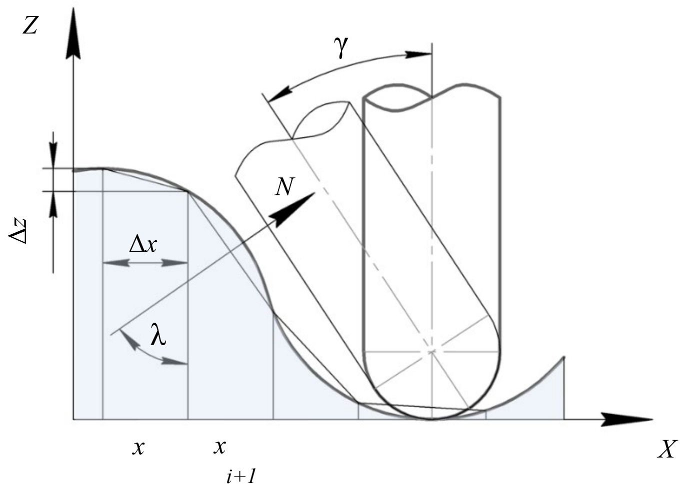

Fig. 1. Scheme for calculating the angle of the normal: N — normal; λ — angle to the normal; Δx — selected step along X axis to calculate the lengths of the polyline curve segments, mm; Δz — distance along Z axis, depending on the step along X axis, mm

With a discretely defined surface profile, the length of the curve describing the profile geometry:

$$S_n = \sum_{i=1}^{n} \Delta S_i. \tag{6}$$

Here, the length of the polyline section $\Delta S_i = \sqrt{\Delta x^2 + \Delta z^2}$.

The roughness of Rz was considered as an output parameter (Fig. 2), taking into account the limitations associated with the trajectories of motion and the angles of inclination of the sphero-cylindrical tool.

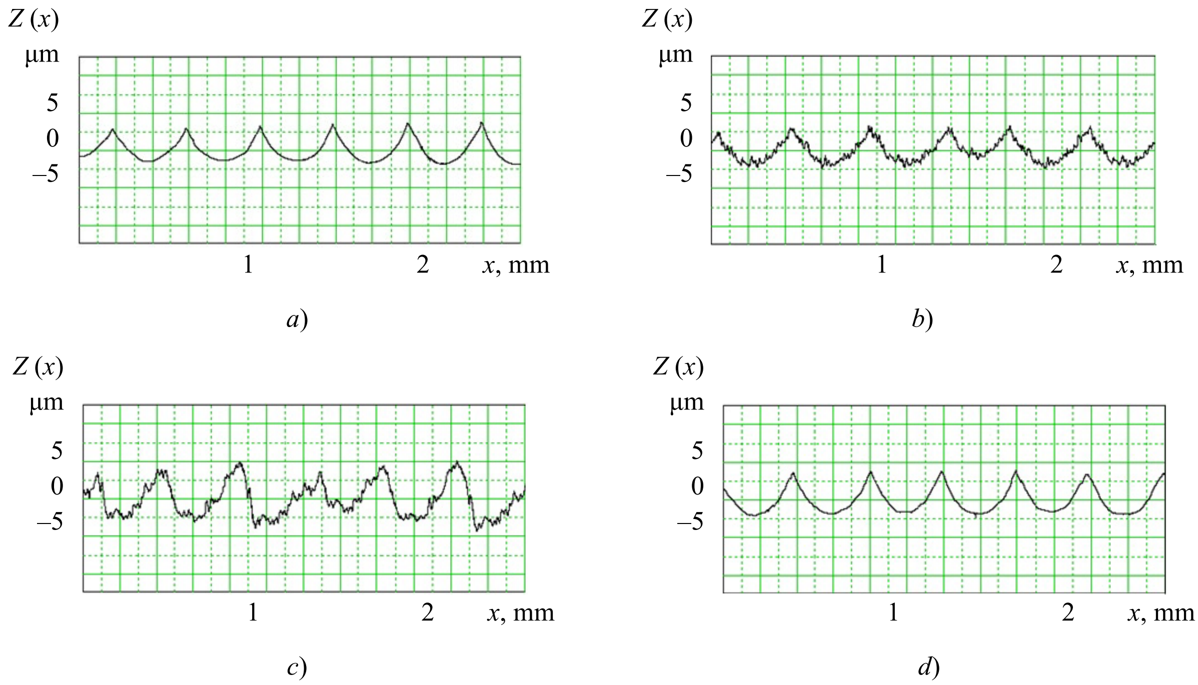

Fig. 2. Profilograms of surfaces obtained with different shaping trajectories at Г = 35°–45°:
a — passing milling; *b* — counter milling; *c* — top-bottom milling; *d* — bottom-up milling

Top-bottom milling is characterized by the greatest amplitude, the unevenness of the resulting surface profile, and is not recommended for shaping with a tool tilted at an angle of 5°–35°.

The roughness selection map (Fig. 3) for *Rz* parameter is based on the results of the given and previous studies [16–19].

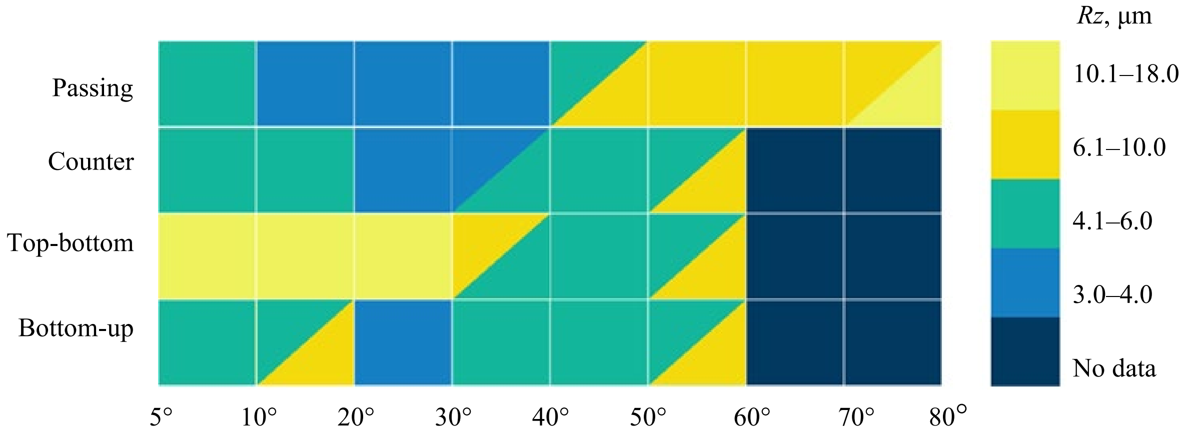

Fig. 3. Roughness selection map

When using CTL, a film was formed on the contact surfaces of the tool and the workpiece material, which helped to reduce adhesive wear. At the cutting speed $V > 70$ m/min, the effect of dynamic friction was reduced. At the same time, the duration of the physico-chemical effect of the medium on the contact surfaces went down, which limited the effect of the use of the CTL (Fig. 4).

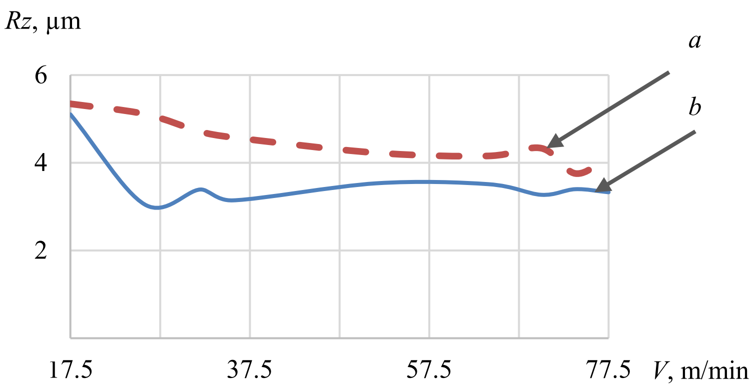

Fig. 4. Dependence of roughness parameter *Rz* on the machining speed: *a* — without CTL; *b* — with the use of CTL

The considered technique was aimed not at establishing critical values of possible orientation angles of a sphero-cylindrical tool for a specific object, but at achieving roughness parameters taking into account the effective cutting speed, feed, and inclination angles for a wide range of parts with concave-convex and linear sections. This approach could provide generalizing and clarifying the ways of optimizing machining. In addition to roughness, the limitations of the minimum effective cutting speed, depending on the effective diameter of the tool, were analyzed. At the same time, the minimum recommended effective cutting speed was (V_{cap}) — 75 m/min.

According to the feed and lateral pitch, the angle of orientation of the tool can correspond to positive and negative values. When calculating, it was considered modulo. Based on the calculated data (Table 2), the surface profile (Fig. 1) was divided into sections. The normal angles were determined, and the trajectories of the shaping movements were assigned to provide the required roughness, taking into account the angles of inclination of the tool.

Table 2

Design parameters for determining the optimal angle of inclination of the tool

n	Δz, mm	Δx, mm	λ,°	$\Gamma = \lambda + \gamma$,°			V_{cap} at $\gamma = 5$
				$\gamma = 1$	$\gamma = 3$	$\gamma = 5$	
1	0.16	0.25	3.59	4.59	6.59	8.59	68.0
2	0.48		10.83	11.83	13.83	15.83	84.4
3	0.82		18.25	19.25	21.25	23.25	99.8
4	1.22		26.01	27.01	29.01	31.01	114.2
5	1.71		34.34	35.34	37.34	39.34	127.2
6	2.38		43.64	44.64	46.64	48.64	138.6
7	3.55		54.82	55.82	57.82	59.82	147.5
8	6.59		69.21	70.21	72.21	74.21	150.7
9	4.56		61.26	62.26	64.26	66.26	150.1
10	2.81		48.39	49.39	51.39	53.39	143.1
11	1.98		38.41	39.41	41.41	43.41	132.7
12	1.43		29.71	30.71	32.71	34.71	120.3
13	1.00		21.73	22.73	24.73	26.73	106.5
14	0.63		14.17	15.17	17.17	19.17	91.5
15	0.30		6.87	7.87	9.87	11.87	75.5
16	0.01		0.32	1.32	3.32	5.32	60.2
17	0.33		7.52	8.52	10.52	12.52	77.0
…	…		…	…	…	…	…
n_i	1.03		22.43	23.43	25.43	27.43	107.8
n_{i+1}	1.47		30.46	31.46	33.46	35.46	121.5

The measured roughness values, taking into account the recommended angles of inclination of the sphero-cylindrical tool and the movement trajectory, are minimal with respect to *Rz* parameter (from 3 to 6 µm). At the same

time, these values correlate with data from other studies (Fig. 3). This allows us to conclude that the proposed method of preparing control information is adequate.

Discussion and Conclusion. The presented technique of selecting the limit values of the orientation angles of a sphero-cylindrical tool can be used to process the SCS with one tool without replacement, taking into account the accepted restrictions. The proposed approach makes it possible to determine the optimal values of the orientation angles of a sphero-cylindrical tool, allowing for the cutting speed and achieving the minimum possible amplitude parameter of roughness Rz.

We considered the situation for surface areas with a total angle of 5°–50° at feed $fz = 0.4$ mm/tooth. In this case, machining along trajectories in the passing direction, from bottom to top and in the opposite direction allowed for roughness in the range of 3–6 µm according to Rz parameter. This was less than the maximum values obtained by 15–30 %. At angles of 10°–40° and the passing processing direction, the minimum values of Rz — 3–4 µm were recorded. The trajectory of top-bottom movement was not recommended for use in final operations due to the significant height of the Rz profile. At the same time, the values of 4.1–6 µm for this trajectory were achieved in a narrow range of angles — 40°–50°.

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